Seeking the progenitors of Type Ia Supernovae

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Abstract. The nature of the progenitor system[s] of Type Ia Supernovae is still unclear. In this contribution I review the projects that have been undertaken to answer this question and the results they have led to. The conclusion is that, as of today, we have reasonable guesses but none of them has yet been proven by direct observations.

Keywords: Supernovae
PACS: 97.60.Bw

THE QUEST FOR THE PROGENITOR'S NATURE

The fact that we do not know yet what are the progenitor system of some of the most dramatic explosions in the universe has become a major embarrassment and one of the key unresolved problems in stellar evolution. [22].

Due to their enormous luminosities and their homogeneity, Type Ia Supernovae (hereafter SN Ia) have been used in cosmology as reference beacons, with the ambitious aim of tracing the evolution of the universe [45, 40]. Despite of the progresses made in this field, the nature of the progenitor stars and the physics which governs these powerful explosions are still uncertain [14]. In general, they are thought to originate from a close binary system [59], where a white dwarf accretes material from a companion until it approaches the Chandrasekhar limit and finally undergoes a thermonuclear explosion. This scenario is widely accepted, but the nature of both the accreting and the donor star is not yet known, even though favorite configurations do exist [5, 33, 53]. But why is it so important to investigate the nature of the progenitor system? Besides the fundamental implications on the cosmological usage of SNe Ia, there are actually several other reasons to bother [22]. First of all, galaxy evolution depends on the radiation, kinetic energy and nucleosynthesis yields of these powerful events. Secondly, the knowledge of the initial conditions of the exploding system is crucial for understanding the physics of the explosion itself. Finally, identifying the progenitors and determining the SN rates will allow us to put constraints on the theory of binary star evolution.

Having in mind why we want to do this, the next question is, as usual, how. A discriminant between some of the proposed scenarios would be the detection of circumstellar material (CSM). However, notwithstanding the importance of the quest, all attempts of detecting direct signatures of the material being transferred to the accreting white dwarf in normal SNe Ia were so far frustrated, and only upper limits to the mass loss rate could be placed from optical [23, 24, 26], radio [32] and UV/X-Ray emission [17]. Claims of possible ejecta-CSM interaction have been made for a few normal objects, namely SN 1999ee [28], SN2001el [56], SN 2003du [11] and SN 2005cg [42]. In all those

cases, the presence of CSM is inferred by the detection of high velocity components in the SN spectra. However, it must be noticed that these features can be explained by a 3D structure of the explosion [28] and, therefore, circumstellar interaction is not necessarily a unique interpretation [42].

Two remarkable exceptions are represented by the peculiar SNe 2002ic and SN 2005gj, which have shown extremely pronounced hydrogen emission lines [13, 1, 41], that have been interpreted as a sign of strong ejecta-CSM interaction. However, the classification of these supernovae as SNe Ia has been questioned [2], and even if they were SN Ia, they must be rare and hence unlikely to account for normal Type Ia explosions [32]. As a matter of fact, the only genuine detection so far seemed to be represented by the underluminous SN 2005ke [34], for which an unprecedented X-ray emission at a 3.6σ-level accompanied by a large UV excess was reported [17]. These facts have been interpreted as the signature of a possible, weak interaction between the SN ejecta and material lost by the donor and used to derive some of its properties [17]. However, a thorough re-analysis of the data has not confirmed these findings [15], thus reconciling the picture with the lack of detection reported at radio wavelengths [49].

Another promising path that has been explored is the one of the so-called entrained material. Very briefly, the impact of the SN ejecta on the companion star is expected to strip its envelope. Part of it becomes entrained in the ejected material and should be observable at late phases in the form of narrow emission lines [58, 10, 51, 6, 21, 25, 29, 31]. So far, no trace of hydrogen (or helium) has been detected in the late spectra of Type Ia SNe and this rules out systems with secondary stars close enough to the exploding WD to be experiencing Roche-lobe overflow at the time of explosion [20].

All the channels explored so far to detect CSM around Type Ia SN progenitors are based on the fact that sooner or later the fast SN ejecta will crash into the slow moving material lost by the system in the pre-explosion phases in the form of stellar wind. This implicitly requires two conditions to be fulfilled: i) there has to be interaction and ii) the amount of CSM and its density must reach some threshold values in order to produce a detectable interaction. Therefore, methods based on ejecta-CSM interaction will not be able to reveal this material if its amount is small, if it is placed rather far from the explosion site or if nova-like evacuation mechanisms are at work [62].

So, the question is whether there exists any other method that does not require interaction with the CSM.

One of them has been proposed and applied very recently and, at variance with those I have described so far, it targets at observing the progenitor system before the explosion [55]. The idea behind this new technique is that different progenitor systems should have different properties when observed in the X-ray domain. More precisely, while in a single-degenerate system X-ray emission is supposed to be a by-product of the accretion process [54], this is most likely not the case for the alternative scenario, where two WDs (henceforth also indicated as double-degenerate) loose momentum through the emission of gravitational waves and eventually merge, producing a thermonuclear explosion [16, 57]. Clearly, in order to be able to apply this method, one needs to have deep, pre-explosion X-ray images of the explosion site, to be compared with analogous images taken after the explosion has taken place. In fact, the detection of an X-ray source at a projected position coincident (to within the errors) with that of the SN is not sufficient to conclude that the X-ray actually came from the progenitor. It is only the

disappearance of that source that would strongly support this conclusion.

This idea has been applied for the first time to the nearby SN 2007on. Based on pre-explosion Chandra archival data, Voss & Neelemans [55] have reported a 4 σ-level detection of an X-ray source at a position which was consistent with that of the SN. The implied luminosity is fully compatible with those of super-soft sources [8], which have been identified as one of the possible channels to Type Ia explosion [54]. In general, the detection of a bright X-ray source spatially coincident with SN 2007on has been interpreted in support the single-degenerate accretion scenario, at least for this particular SN [55].

The site of SN 2007on was re-visited by Chandra about six weeks after the SN reached maximum light and the astrometry of the field refined [46]. After this re-examination two main facts have emerged: i) there is a statistically significant offset between the pre-explosion X-ray source and the SN position; ii) the X-ray source is still there after the SN explosion, but its luminosity has dimmed by about a factor four [46]. In the light of the fact that no Type Ia SN has ever been detected in X-rays at any epoch [17], this indeed questions the conclusions originally inferred for the nature of the source and its identification as the progenitor of 2007on. Clearly, only further, deep Chandra observations will allow us to reach a firmer conclusion [46]. This technique has been applied to three other nearby Type Ia SN, for which pre-explosion Chandra observations were available, but no X-ray source was detected at the SN positions [55]. Even though its application has the availability of archival, X-ray data as a mandatory pre-requisite, it is certainly a promising tool to investigate the nature of Type Ia progenitors.

NOT THROUGH HYDROGEN: YET ANOTHER METHOD TO DETECT CSM IN IA'S

While investigating the effects of a close-by, dusty environment on the light curves and spectra of Type Ia SNe [35, 36], we saw another possibility of revealing possible CSM without the need of having matter interaction. In fact, since in SNe Ia the UV flux bluewards of 350 nm undergoes severe line blocking by heavy elements like Fe, Co, Ti and Cr [39, 27], they are able of ionizing possible CSM only within a relatively small radius. Once the UV flux has significantly decreased in the post-maximum phase, if the material has a sufficiently high density it recombines, producing time-variable absorption features. Of course, if the material where these features arise is reached by the fast moving ejecta, it will be shocked and ionised, causing the disappearance of such absorptions. Among all possible inter/circumstellar absorption lines, the ubiquitous Na I D lines are the best candidates for this kind of study. In fact, besides falling in an almost telluric absorption-free spectral region, they are produced by a very strong transition, and hence detectable for rather small gas column densities. In addition, the ionization potential of Na I is low (5.1 eV), and this ensures that even a weak UV field is able to have a measurable effect on its ionisation, without the need for direct interaction.

With this idea in mind, the experimental path was rather clearly traced: obtain multi-epoch, high-resolution spectroscopy of the next bright SN Ia and look for absorption-line variability. The first chance to test our idea came when SN 2006X was discovered in the Virgo Cluster spiral galaxy M100 on February 4, 2006. A few days later, the object
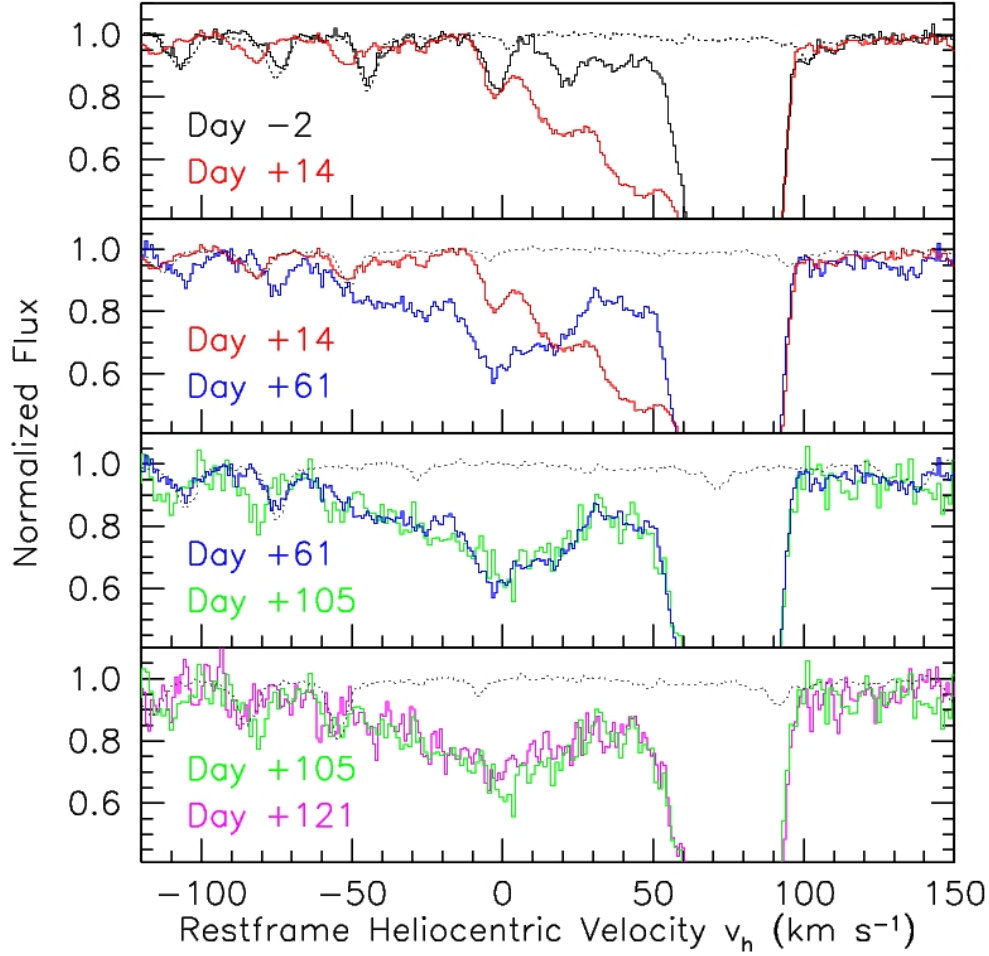
FIGURE 1. Time evolution of the sodium D_2 component region as a function of elapsed time since B-band maximum light. In each panel the dotted curve traces the atmospheric absorption spectrum.

was classified as a normal Type Ia event occurring 1–2 weeks before maximum light and suffering substantial extinction [43] . Prompt Very Large Array (VLA) observations have shown no radio source at the SN position, establishing one of the deepest and earliest limits for radio emission from a Type Ia, and implying a mass-loss rate of less than a few 10^{-8} $M_{\odot}$ yr^{-1} (for a wind velocity of $10\,km\,s^{-1}$) [50]. The SN was not visible in the 0.2-10 keV X-rays band down to the SWIFT satellite detection limit [17]. All of this made of SN2006X a perfect candidate to verify our idea. The observations started on February 18th and were carried out with the Ultraviolet and Visual Echelle Spectrograph (UVES) mounted at the Very Large Telescope on four different epochs, which correspond to days -2, $+14$, $+61$ and $+121$ with respect to B-band maximum light. Additionally, a fifth epoch (day $+105$) was covered with the High Resolution Echelle Spectrometer mounted at the 10m Keck telescope. The data show a wealth of interstellar features [9], but the most remarkable finding is the clear evolution seen in the profile of the Na I D lines [37].

In fact, besides a strongly saturated and constant component, arising in the host galaxy disk, a number of features spanning a velocity range of about 100 km s^{-1} appear to vary significantly with time (see Figure 1). SN2006X is projected onto the receding side of the galaxy, and the component of the rotation velocity along the line of sight at the apparent SN location is about +75 km s^{-1}, which coincides with the strongly saturated NaI D component, the saturated Ca II H&K lines, and a weakly saturated CN vibrational band. This and the lack of time evolution proves that the deep absorption arises within the disk of M100 in an interstellar molecular cloud (or system of clouds) that is responsible for the bulk of reddening suffered by SN2006X. In contrast, the relatively blue-shifted structures of the Na I D lines show a rather complex evolution. Without going into the details (the reader is referred to [37]), these findings were interpreted as a solid evidence of CSM expanding at velocities that span a range of about 100 km s^{-1}, placed between 10^{16} and 10^{17} cm from the explosion site and ejected from the progenitor system in the recent past. This almost certainly rules out a double-degenerate scenario for SN2006X, where the supernova would have been triggered by the merger of two CO white dwarfs. In this case, no significant mass loss would be expected in the phase immediately preceding the supernova and, thus, a single-degenerate system is the favored one for SN 2006X[1].

The observed structure of the circumstellar material could be due to variability in the wind from the companion red giant, since considerable variability of red giant mass loss is generally expected [61]. A potentially more interesting interpretation of these distinct features is that they arise in the remnant shells (or shell fragments) of successive novae, which can create over-density regions in the slow moving material released by the companion, also evacuating significant volumes around the progenitor star [18, 19, 62]. The calculations have difficulty in matching the velocities in our observations if the nova shells are decelerated in a spherically symmetric wind, in the sense that the measured velocities are too small. However, if the wind is concentrated towards the orbital plane this discrepancy could be removed, since the nova shell would be more strongly decelerated in the equatorial plane; in that case we would be observing the supernova close to the orbital plane. Not only might this be expected a priori, but observations of the 2006 outburst of RS Ophiuchi show that the nova ejecta are bipolar and that there is an equatorial density enhancement which strongly restrains the expansion of the nova shell [30], providing some support for such a scenario.

Interestingly, short-lived heavy element absorption systems have been reported for a number of novae near maximum light and interpreted as the signature of circumbinary material [60]. It has also been suggested that very early multi-epoch, high resolution spectroscopy of Type Ia SNe might be used to disentangle between different progenitor

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[1] However, I think it is fair to report here a private communication I received from A.V. Tutukov (May 2008). He maintains that in a binary system formed by two degenerate stars, the common envelope can survive for about 10^4 years. This time is sufficient for the two WDs to merge via gravitational waves radiation if the separation between the two components is within a suitable range. Based on his calculations, he concludes that about one third of all Ia could form in double degenerate systems still embedded in their common envelopes and, therefore, produce absorption features similar to those seen in SN 2006X at the time of explosion. For this reason, he reckons, these findings are not necessarily excluding a double degenerate system for this particular event.

scenarios through the study of those systems [60]. Clearly, in the case of a nova, the spatial scales that can be probed by the observations are much smaller than in the case of a SN, where the fast expanding ejecta sweep some 20 AU during the first day after the explosion. This, together with the fact that a SN is typically discovered several days after the explosion, makes it very difficult to study the progenitor system down to circumbinary scales. Even in the hypothesis this material has not yet been reached by the ejecta, being so close to the explosion it is most likely completely ionised by the SN radiation field.

PROBLEMS AND PERSPECTIVES

One problem with the scenario proposed by Patat et al. [37] to explain the behavior seen in SN 2006X is that even though the UV field produced by a Type Ia explosion is relatively weak, the ionisation rate is still sufficiently high to keep sodium fully ionised in a spherically symmetric wind produced by a red giant for more than a month at distances smaller than 10^{17} cm. This implies that the time-evolving Na I D lines detected in 2006X cannot arise in the wind of a red giant star [7]. For this reason, N. Chugai has proposed that these features have nothing to do with the circumstellar environment, arise in clouds placed at distances larger than 10^{17} cm, and their variations are due to a purely geometrical effect [7]. This possibility was discussed and excluded by Patat et al. [37], based on the fact that while the Na I D features vary, Ca II H&K do not. It must be noticed that, in order for the geometrical effect to explain the observed behavior, a rather ad-hoc cloud geometry and chemical composition (and/or physical conditions) are required [7]. One prediction that follows from the scenario proposed by Chugai is that these time-variant features should have a higher probability of being detected in highly reddened events [7]. In this respect, it is interesting to note that a study conducted on a sample of low resolution spectra of 31 Type Ia SNe has shown that only two SNe displayed Na I D variability, namely SNe 1999cl and 2006X, the two most highly reddened objects of the sample [3]. However, another highly reddened SN included in the sample (SN 2003cg) did not show any trace of variability.

Even though the results obtained with multi-epoch, high-resolution observations of SN 2006X have already triggered a couple of similar studies [38, 47], the sample is simply too small to allow any firm conclusion. For this purpose we have started a program at the VLT with the aim of obtaining data for a fair number of nearby events. During the first year of activity three SNe have been observed, i.e. 2008ec, 2008fp and 2008hv. The data will be presented soon, but here I can anticipate that none of them has shown any signs of variability, even if the first two objects suffered a substantial extinction within the host galaxy, as witnessed by saturated Na I D lines. So far, only another case, even though not so extreme as SN 2006X, has been found [48]. In fact, multi-epoch, high resolution spectroscopy of SN 2007le has clearly shown variability in the Na I D profiles, while the Ca II H&K profiles did not show any evolution[2].

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[2] Unfortunately, nothing can be said about the behavior of Ca II H&K in SN 1999cl, the only other known case of variability [3].

This dicothomy in the behavior of Na I vs. Ca II lines is probably the key fact in the understanding of what the physical reason for the observed variability is. If more cases are found, the chances this is due to a fortuitous series of coincidences will become negligibly small. What we have seen in 2006X is far from being completely understood and we are certainly left with more questions than answers.

After reviewing all the methods that have been proposed and applied so far to directly[3] unveil the nature of Type Ia SN progenitors, it is clear that none of them has given a satisfactory picture and the systems which give rise to one of the most catastrophic events in the universe remain concealed. The only thing we know is that they must be surrounded by tiny amounts of material, otherwise we would have detected them through the interaction with the SN ejecta. Whether this gas is in the form of dense clumps, an equatorial torus, nested and fragmented shells or bipolar structures remains to be clarified.

I believe that by now we are all convinced that there is more than one channel leading to the same explosive theme, on top of which nature adds some variations, as the non perfect homogeneity of SNe Ia seems to tell us. Rather than the end of an old story, I consider the most recent findings in this field as the beginning of a new one.

ACKNOWLEDGMENTS

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[3] Note that there are other, less direct paths to approach this problem, based for instance on the chemical yields, delay times and rates of Type Ia explosions, which I have not considered here. See for instance [12] and references therein.

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